The Space Elevator

Bradley C. Edwards, Ph.D.: Funded by NIAC

Concept: A cable with one end attached to Earth and the other 100,000 km up in space that can be ascended by mechanical means.

Benefits:
- Reduction of launch costs to <1% of rockets
- Expandable to larger and distributed (Mars) system
- Capable of launching large, fragile payloads
- Large capacity per launch and over time

Basic system consists of:
- Cable - carbon nanotube composite
- Anchor - ocean going platform (*Sealaunch)*
- Counterweight - deployment satellite and climbers
- Power system - laser power beaming (*Compower)*
- Climbers - off-the-shelf components
- Cable deployment requires 7 Shuttles and >200 climbers

Specifications:
- Cable - 100,000 km (3X longest trans-oceanic cable), 30 cm wide, microns thick
- Cable capacity - 20,000 kg
- Destinations - LEO, GEO, other planets
- Schedule - operational in 15 to 30 years
- Cost - ~$40B for construction

Required development:
- Mass production of long carbon nanotubes
- Carbon nanotube composites

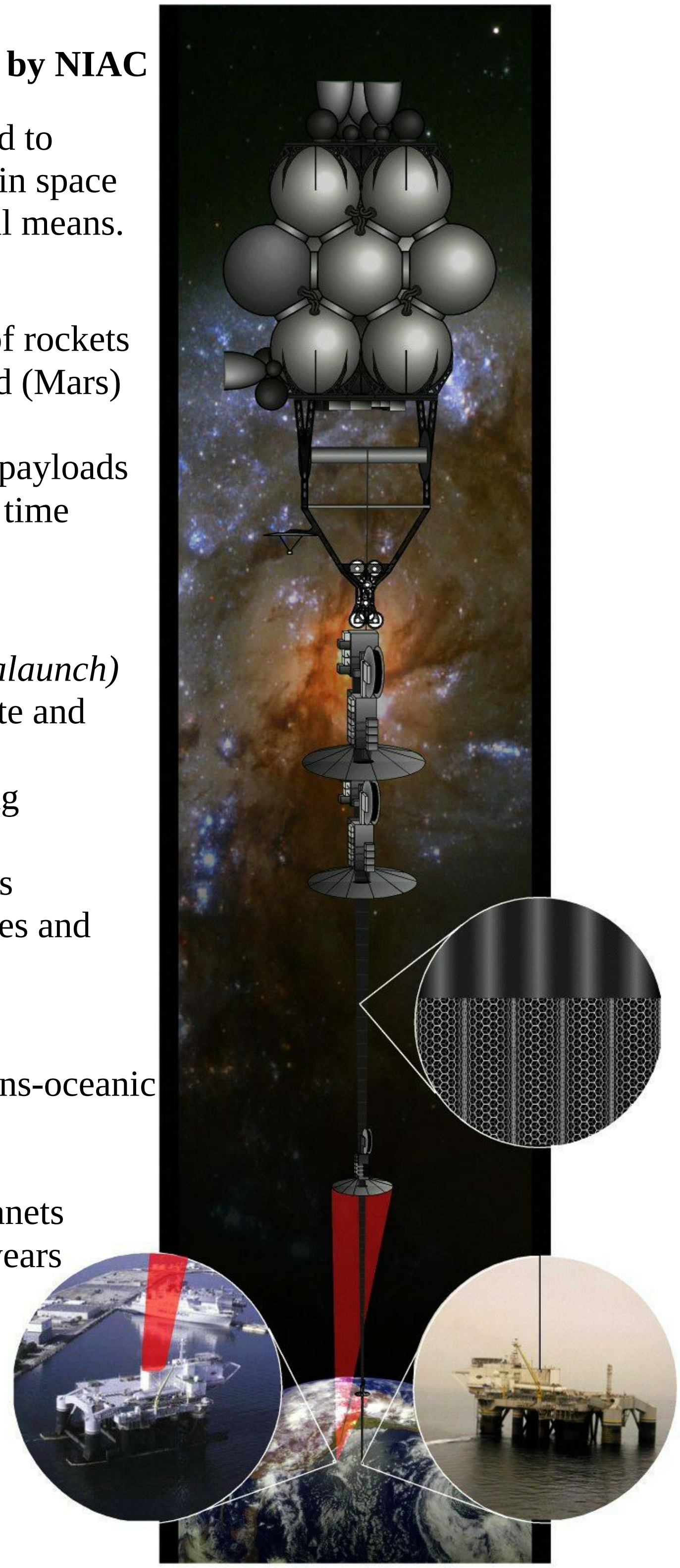

Figure 1: Artists conception of the space elevator developed in our NIAC Phase I work..

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Abstract

The primary limiting factors on human/robotic exploration are the high cost and performance limitations of chemical launch systems. The space elevator, a cable that can be ascended by mechanical means from Earth to space, would reduce the cost of getting into space by a factor 100 or more while increasing launch capabilities dramatically. Such a revolutionary system as the space elevator would allow for a greatly expanded human/robotic exploration program. Under a NIAC grant we have laid the technical groundwork by examining all aspects of a first elevator including: the carbon nanotube composite cable design, deployment using conventional launch systems, climber design and operation from the power beaming to the electric drive motors, the anchor station, applications, construction budget, construction schedule, environmental hazards from lightning, atomic oxygen, meteors, and wind to malfunctioning climbers. In our assessment an operational space elevator (20,000 kg capacity) could be built in the next 15 years with an aggressive program and at a cost of roughly $40B. The most pressing technological development is the continued work on carbon nanotubes and composites for the cable construction. Our current efforts will answer many of the design and implementation questions that remain, provide direction for future research and be crucial for future funding and programmatic decisions. Following deployment of the first space elevator large robotic probes could be sent inexpensively to solar system destinations or Earth orbit. Within 30 years hundreds of humans could be permanently stationed in high-Earth orbit or on Mars by utilizing the first elevator to produce larger cables and elevators for other locations such as Mars. Both human exploration and colonization of nearby locations and extensive robotic exploration of distant locations would be enabled by the space elevator. The specific science that would be enabled includes on-site studies of Mars, rigid, space-based, kilometer-size, mirrors and interferometers, 0-g production, geosynchronous atmospheric and space studies at any altitude, and extensive, long-term, human, plant and animal physiology studies. What we have listed here is only the tip of the iceberg once an inexpensive, high-capacity system is in place.

Advanced Concept Description

The space elevator has appear in various forms in literature for decades. The first appearance in modern form with a technical discussion appeared in 1960 (Artsutanov) in a Russian technical journal. In the following years the concept appeared several times in technical journals (Isaacs, 1966; Pearson, 1975; Clarke, 1979) and then began to appear in science fiction (Clarke, 1978; Stanley-Robinson, 1993). The simplest explanation of the space elevator concept is that it is a cable with one end attached to the Earth's surface and the other end in space beyond geosynchronous orbit (35,800 km altitude). The dominant, competing forces of gravity at the lower end and outward centrifugal acceleration at the farther end keep the cable under tension and stationary over a single position on Earth. This cable, once deployed, can be ascended by mechanical means to Earth orbit. To place a spacecraft in geosynchronous orbit the climber simply ascends to that altitude and releases its payload. To place a spacecraft in any other circular Earth orbit the payload would require a small engine to achieve the proper orbital

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velocity. If a climber proceeds to the far end of the cable it would have sufficient energy to escape from Earth's gravity well simply by separating from the cable. The space elevator thus has the capability in theory to provide easy access to Earth orbit and most of the planets in our solar system (Pearson, 1975).

In comparison to many fields of active research there has been little quantitative work done on the space elevator. Pearson and a few others did some quantitative work in the 60's and 70's but in recent years the space elevator has been largely ignored in the technical journals. An alternative area of research in sky hooks (a cable between two orbits for orbital transfer) has emerged and produced some interesting work (*Proceedings of the Tether Technology Interchange Meeting*, Huntsville AL, Sept. 1997). Even though the basic ideas are similar, the construction, utility, problems and operations are dramatically different between space elevators and sky hooks. Because of these extensive differences we will not discuss the sky hook further here.

Our NIAC Phase I work laid out a detailed description of a possible space elevator program (Edwards, 2001) extending the work found in Edwards, 2000. A small, carbon-nanotube-composite cable capable of supporting 619 kg payloads would be deployed from geosynchronous orbit using seven shuttles and liquid- or solid-fuel-based upper stages (assembled in LEO). Climbers (207) are sent up the initial cable (one every 4 days) adding cables to the first to increase its strength. After 2.3 years a cable capable of supporting 20,000 kg payloads would be complete. The power for the climbers is beamed up using a free-electron laser and adaptive optics system identical to the one designed by Compower and received by photocells. The spent initial spacecraft and climbers would become counterweights at the space end of the 91,000 km long cable. An ocean-going platform, based on the current *Sea Launch* program, is used for the Earth anchor. This anchor is mobile and able to move the cable out of the way of low-Earth orbit satellites. The anchor location is in the Pacific Ocean, roughly 1500 km west of the Galapagos Islands to avoid lightning, hurricanes, strong winds, and clouds. The specific cable design would be a curved and tapered ribbon with a width increasing from Earth to geosynchronous and back down to the far end. Deviations in the cable's cross-sectional dimensions would be implemented to reduce the risk of damage from meteors and wind. All of the raw technologies required to construct the space elevator may be ready in the coming decade. Carbon nanotubes require the most development but they are now produced in the lab with characteristics close to that needed for construction of a space elevator (see figure 1; Li, 2000; Cheng, 1998; Yu, 2000a; Yu, 2000b). Major risk of damage to the cable comes from meteor impacts and atomic oxygen erosion, both can be mitigated through several methods.

The objective of our NIAC Phase I study was to examine all aspects of the space elevator from the basic design and challenges to the overall system cost. There were a large number of areas to investigate, calculations to be done and problems to solve. The specific results of our Phase I study included:

- Finding a power beaming system using available laser and adaptive optics technologies that will work from sea level and provide the >2MW of power required (Compower is currently building this system for powering geosynchronous satellites)
- Examining the trade-off between laser-based and millimeter-based power beaming systems

- Designing cables on scales of microns to kilometers to survive the environment and minimize the overall mass (we defined the overall shape, the optimal width and length, specific modifications to address environmental problems, etc.)
- Calculating the wind loading on our proposed cable and coming up with overall system and cable modifications that will eliminate any concern of wind damage
- Examining the problem of low-Earth objects impacting on the cable. We calculated the impact rates on the cable. To avoid this problem we found we can track the low-Earth orbit objects and move the cable out of their path. Two possible tracking systems and avoidance requirements were discussed in detail (Loftus, 1993).
- Finding two suppliers of carbon nanotubes including one that makes straight bundles over 4 cm long (Cheng, 1998) with individual nanotube tensile strengths of 22 GPa (see figure 1; Li, 2000). We received several nanotube bundles for examination and ordered 4 grams of carbon nanotubes for composite studies. We also found references to nanotubes with tensile strengths of 63 GPa (Yu, 2000a) which is sufficient to build a space elevator

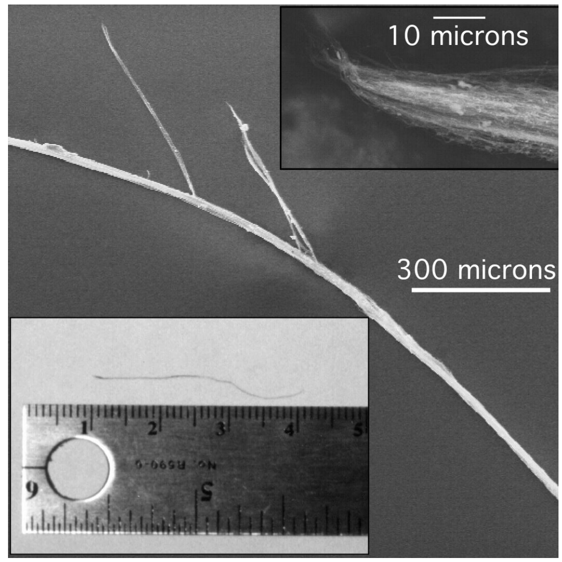

Figure 1: A carbon nanotube bundle. Carbon nanotubes produced by the system had measured tensile strengths of 22 GPa.

- Examining the atomic oxygen erosion problem and found a possible solution based on Long Duration Exposure Facility (LDEF) spacecraft data. Coatings of metal or other material can be used to eliminate the damage
- Finding the optimal anchor location which is an area in the Pacific west of the Galapagos islands (no lightning, little wind, no hurricanes, few clouds, and on the equator)
- Illustrating the possible scenarios in which the space elevator could fall and discussed methods to mitigate the risks and damage (saving malfunctioning climbers, designing the cable to break-up on re-entry, comparing the in-fall volume of material with natural phenomenon)
- Quantifying aspects of induced oscillations, radiation damage, and induced electrical currents to show these are not problems at least in the scenario we proposed
- Working out a deployment scenario using current launch systems and technologies that requires only seven shuttles and available upper stages (Centaur and/or solid fuel based)
- Working out the complex orbital mechanics involved in deploying the initial cable. (It is a unique orbital mechanics problem that requires care to get the cable deployed properly without coming down.)
- Finding a mobile anchor design based on oil drilling platform technology and currently in use in the *Sea Launch* program (the existing technology is almost ideal for our purposes)
- Working out the meteor fluxes and damage rate for our proposed cable (Both normal and grazing incident impacts verses size were examined as well as finding laboratory data on all of these types of impacts – Lamontage, 1999; Taylor, 1999)

- Working out a cable design that will survive the expected meteor flux (a curved ribbon with alternating segments of composite and bare nanotubes)
- Examining the current state of spooling technology (Spooling rates)
- Determining which solar system destinations are accessible for different elevator lengths (With our proposed system Venus, the moon, Mars and Jupiter are accessible with only plane change and attitude correction engines)
- Laying out a scenario for deploying a Martian elevator. Our proposed scenario is to construct the entire Martian system in Earth orbit along side the Earth elevator. This Martian system would then be spooled, taken to the far end of the Earth elevator and launched to Mars. Upon arrival at Mars the elevator would deploy and anchor itself. This system could be constructed without placing men on Mars first and could provide an inexpensive, reusable system for transportation to and from Mars.
- Developing a detailed deployment schedule that illustrated it could be possible to have the first space elevator operational six years after the technology is ready (the technology could be ready in the next ten years).
- Working out a design for the climbers that fits the mass and power budget (a design study of a DC motor specifically for this purpose was included)
- Laying out various program options including different launch vehicles, cables sizes, scheduling, future utilization, etc. and discussed the impacts and returns for each of these options.
- Refining the budget estimates for the entire system and found the space elevator might be constructed for less than some current space programs ($40B)

The bottom line is that we examined the entire system in detail and found a space elevator design that will work, a method to deploy the cable, and no specific reasons why a space elevator can't be built. The major hurdle is production of the cable. It was also found that the space elevator will not only be able to be done for less than some current programs but it could be financially self-supporting (including recovering the initial construction costs) within the first few years of operation. The recurring costs are: 1) climbers, 2) power beaming system operation, 3) low-Earth object tracking system operation, and 4) anchor operations. For the initial space elevator these costs can be 1/10 to 1/100 or less of the cost of conventional systems per launch. A detailed write-up of our work and conclusions is on the Internet (www.niac.usra.edu/studies/) and is being published in paperback (Edwards, 2001).

However, our Phase I work did not answer all of the questions. It clearly demonstrated that there are solutions but did little testing of the specific hardware or scenarios we proposed. In Phase II we plan to concentrate on working out many of the details we were unable to address in Phase I and testing the design options. The Phase II work is absolutely critical for future planning and design studies. Prior to Edwards, 2000, there was no published quantitative analysis of the difficulty in building a space elevator. Even after reading Edwards, 2000, a NASA official would be going out on a very weak limb to suggest constructing a space elevator. With our Phase I final report in hand, a policy maker could put forth a strong argument that some type of study related to the space elevator is worthwhile. However, that same policy maker would be hard-pressed to state which particular studies require federal funding to insure no critical issue is missed, within which decade a space elevator could be built, that all of the feasibility issues have been addressed or what's the fastest and best way to build a space elevator. Our Phase II work will answer any remaining basic feasibility questions, define the critical technologies that require development funding from NASA, quantify the effort required to get the technologies ready, complete a thorough examination of the possible design options, their costs and benefits, and refine the budget estimates for construction of the space elevator. With our final Phase II report NASA will be able to make quick, informed decisions on whether a space elevator should be pursued, how to pursue it, how much it will cost, when they can expect it to be completed and what is the likelihood of success.

The primary areas that we are attacking in our NIAC Phase II include:

- Large-scale nanotube production: to study the complications in producing the tons of 100,000 km long cables after the technology for constructing short lengths is developed
- Cable production: Producing several short lengths of cable to begin development of the required carbon nanotube composite technology and for use in the studies below
- Cable design: Continue work on the design of the cable and conduct high-velocity impact, atomic oxygen and wear tests on the carbon nanotube segments produced in #2 above.
- Power beaming system: Continue design studies on the power beaming system and improve our understanding of the interactions between the power beaming system and other components of the elevator
- Weather at the anchor site: Conduct detailed, long-term studies of the weather at the proposed anchor location to quantify the risk of damage to the cable from weather
- Anchor design: continue discussions with the Sealaunch program to understand the performance of the proposed platform and its impacts on other components.
- Environmental impact: Understand the implications of a stable cable or a failed cablle on the environment
- Placing payloads in Earth orbit: Quantify the applications of the elevator for use in placing payloads in Earth orbit
- Elevators on other planets: conduct preliminary designs for systems deployed at other locations and how the systems can interact to create a complete transportation system
- Possible tests of system: produce preliminary designs for experiments to test the system feasibility
- Major design trade-offs: Lay out possible design options and their impact on the cost, schedule, risk and performance
- Budget estimates: Improve original cost estimates
- Independent review of program: conduct a conference and publish the results to distribute the design information.

Significance of the Space Elevator Concept

The significance of this initial work is considerable. If feasible, the space elevator would be an entirely new method for getting into space. Even the first, small cable that we examined (20,000 kg lift capacity every four days) would be able to launch NASA missions to Earth orbit, the moon, Mars, Venus and Jupiter without the launch forces, risk or cost of a conventional system. The first space elevator would have greater than 2.5 times the capacity of any current launch system, at 1% of the cost, for placing payloads in geosynchronous orbit or sending them to other solar system destinations. The space elevator would allow for the launch of large fragile structures such as radio dishes, large diameter mirrors or even extremely long (up to kilometers), rigid booms for interferometry experiments. The elevator would also allow for retrieval and repair of spacecraft in geosynchronous orbit, stationary studies at any altitude, and private-industry, recreational activities. A second generation, larger space elevator (operational 20 – 35 years from now) would allow for extensive human activities in space including a large, manned geosynchronous station and less risky and less expensive colonization of Mars. Long-term future activities (100 years) would see man expand across the solar system.

Required Development

Although considerable progress has been made over the last two years in developing the space elevator concept, substantial requirement is still needed.

The top priority is development of carbon nanotube production and use in composites. This area of research is progressing extremely rapidly and is near what is required for the space elevator. Production techniques for carbon nanotubes are now at the level where long nanotubes of the quality we need can or soon will be made in the laboratory with techniques that are scalable. Commercial companies now ramping up to produce large quantities of carbon nanotubes (CNI: 2000kg/week). Incorporating these nanotubes into a composite is the next most critical area of development. Progress in this area has been made and with some financial support should achieve the level required for the space elevator in the very near future. The last area of development related to the cable is its mass production. This development should be done by and based on the textile and other large industries currently dealing with similar problems.

Additional development is required in the overall design and operation of the space elevator and feasibility testing of the system and components. This has been discussed above.

Most of the remaining components of the space elevator are well along in there development and some are being used in operational systems.

Personnel

Bradley Carl Edwards

Dr. Edwards received his Ph.D. in physics in 1990 from the University of Wisconsin – Madison. Since receiving his degree Dr. Edwards has worked at Los Alamos National Laboratory in advanced space technology. Dr. Edwards has published original design research on the space elevator and led the NIAC Phase I effort studying the space elevator which will be published in book form in February, 2001. His experience on numerous space missions including conception and design of unique and innovative lunar and Europa orbiter missions and successful construction of the first optical cryocooler starting in a non-existent field with only a basic theory has illustrated Dr. Edwards' capabilities to excel in challenging programs. For his efforts Dr. Edwards has received a distinguished performance award and letter of commendation from the DOE for his work, has served on organizing committees for various conferences including SPIE and NASA's science definition and instrument definition teams for NASA's Europa orbiter mission.

Dr. Edwards has over 40 publications including:

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